Proceedings of HT-FED04
2004 ASME Heat Transfer/Fluids Engineering Summer Conference
July 11-15, 2004, Charlotte, North Carolina USA

HT-FED04-56528

# DEVELOPMENT AND EXPERIMENTAL VALIDATION OF AN EXERGY-BASED COMPUTATIONAL TOOL FOR DATA CENTER THERMAL MANAGEMENT

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## ABSTRACT

The recent miniaturization of electronic devices and compaction of computer systems will soon lead to data centers with power densities of the order of 300 W/ft$^2$. At these levels, traditional thermal management techniques are unlikely to suffice. To enable the dynamic smart cooling systems necessary for future data centers, an exergetic approach based on the second law of thermodynamics has recently been proposed. However, no experimental data related to this concept is currently available. This paper discusses the development and subsequent validation of an exergy-based computer model at an instrumented data center in Palo Alto, California. The study finds that when appropriately calibrated, such a computational tool can successfully predict information about local and global thermal performance that cannot be perceived intuitively from traditional design methods. Further development of the concept has promising potential for efficient data center thermal management.

Keywords: exergy, availability, data centers, thermal management, experimental validation.

## INTRODUCTION

Rita Colwell, Director of the National Science Foundation, once observed: “In many ways, the history of computing is an astonishing and very modern tale. So much has been telescoped into such a short time, compared to the centuries of stately development that are typical of the more traditional and older sciences” [1]. Indeed, the rapidity and magnitude of change witnessed in information technology is of an unparalleled nature. From the lone ENIAC computer of 1946, the number of computers around the globe will have increased to almost two billion by the year 2008 [2]. Similarly, the Internet has grown from a fundamental four-nodal design to a global entity connecting more than 600 million unique users [3, 4]. The growth is not expected to abate anytime soon either: with almost 200 million hosts already online, the number of hosts continues to increase at an average of 40% per year [5]. Consequently, more than a quarter of the world’s population now has instantaneous access to information that was previously unobtainable – the weather at the beach and on the moon, the results from an Olympics event halfway around the world, and the latest quotes from international money markets – all from within the comfort of their living rooms. The phrase ‘information is everywhere’ is certainly no longer a cliché [6].

Unfortunately, along with an increase in the amount and speed of data processing, the amount of heat released from computing equipment has also increased correspondingly. During the last decade, the power dissipated per unit area of a chip has increased by an order of magnitude; microprocessor heat dissipation has similarly gone up by a factor of ten [7]. Heat output from servers and other computing equipment has also risen, and the 4-5 kW computer racks of today are likely to become 15 kW racks in the near future [8]. It is anticipated that a typical data center housing computing, networking and storage equipment will soon have to cope with heat dissipation rates in excess of 300 W/ft$^2$ [9]. At these densities, existing cooling systems in a data center that houses five thousand 10 kW racks over a 9200 m$^2$ (100,000 ft$^2$) area will require approximately 20 MW of electricity and cost an additional $18 million per year [9]. Clearly, data center thermal performance is of the utmost interest, both for purposes of environmental energy conservation and potential economic savings.

## NOMENCLATURE

| | |
|---|---|
| $C_p$ | Specific heat at constant pressure, J/kg-K |
| h | Specific enthalpy (per unit mass), J/kg |
| $\dot{m}$ | Mass flowrate, kg/s |
| $\dot{Q}$ | Rate of Heat Generation, W |
| s | Specific entropy (per unit mass), J/kg-K |
| T | Absolute Temperature, K |
| $\psi$ | Specific exergy (per unit mass), J/kg |
| $\Psi$ | Total exergy of system, J |
| $\dot{\Psi}_d$ | Rate of Exergy destruction, W |

Subscripts

| | |
|---|---|
| 0 | property evaluated at ground state |
| CRAC | Computer Room Air-Conditioning unit |
| in | inlet state |
| ini | initial state |
| out | exit state |
| P | property at state of processor |
| rack | property at rack location |
| sup | property at supply condition to data center (vent tile) |

## BACKGROUND

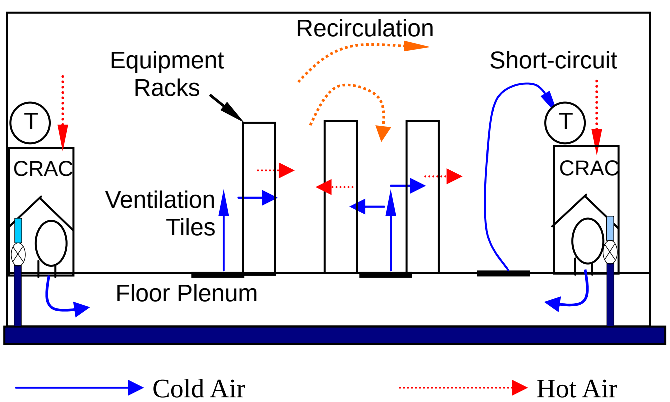


**Figure 1**. Cooling modes and inefficiencies occurring in a typical data center.

Figure 1 shows the typical layout of a data center cooling system. Computer Room Air Conditioning (CRAC) units supply cold air to the data center to remove the heat generated from computing racks and other equipment. The best practice is to divide the physical airspace of the data center into cold and hot aisles, so that low-temperature air enters the room from the CRAC, gets heated up in the rack, and then enters the hot aisle [10]. Usually a raised floor design is used to create a pressurized underfloor plenum that delivers the flow to the room via perforated tiles in the cold aisle. Some data centers may have a supply of cold air from the top and/or sides of the equipment and exhaust it from the bottom, but the vast majority of data center cooling systems consist of a raised floor design as described above.

The warm air from the hot aisle is removed from the computing environment either via a room return or ceiling return mechanism. This air is returned to the CRAC unit, which is then refrigerated by a chilled water stream or other thermal work input mechanisms before being resupplied to the data center environment at a colder temperature.

While sufficient for the low heat loads of previous decades, the static cooling system described above will soon become insufficient. For example, the following problems are encountered with traditional data center cooling systems [8, 9]:

- The mixing of hot and cold streams of air results in a waste of energy. Phenomena shown in Fig. 1 such as recirculation and short-circuiting tend to reduce the efficiency of data center thermal management systems. Moreover, the exact locations of mixing are difficult to identify using traditional thermal analysis techniques.
- Even though the overall environment inside the data center may be reasonably cool, local hotspots may exist. Under such a scenario, conservative designs based on single-input, single-output control system can potentially cause unnecessary shutdown of the entire system or an unneeded increase in cooling.
- Internal and external environmental conditions and their impact on thermodynamic efficiency are typically not assessed during data center operation.

It has been demonstrated that an exergy-based approach has the potential to resolve several of these issues [11]. To further explore this concept, a three-dimensional computer model of an instrumented data center in Palo Alto, California was developed. The next section discusses the development of this model.

## MODELING CONSIDERATIONS

To determine the exergy loss in the physical airspace in the data center, a finite volume analysis should be performed on the physical room space of the data center as shown in Fig. 2. The number and size of the cells chosen for the analysis depends on the thermal variability encountered within the system. It is essential to choose a cell size that is small enough to capture field variations at length scales of room sub-region dimensions. Smaller cell sizes will automatically lead to greater accuracy and lower error, but the correlation between cell size and computational time should be duly considered while choosing cell dimensions. A larger number of cells results in more complex mathematical systems, which in turn increases the time and computational power required to obtain the desired solutions. Thus, cell sizes should be chosen as a compromise between the required level of granularity (or the degree of accuracy necessary) and the desired speed of computation.

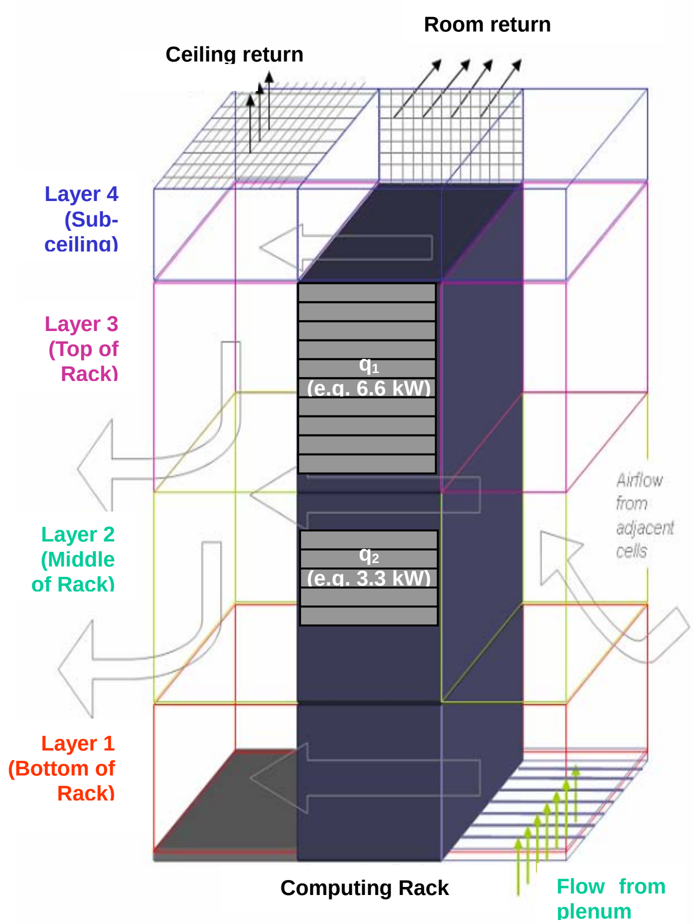


**Figure 2.** Finite volume analysis in a data center [11].

The exergy loss at steady state in any single cell of the airspace can be determined by performing a simple exergy balance to obtain [12]:

$$\dot{\Psi}_d = \sum\left(1-\frac{T_0}{T_P}\right)\dot{Q} + \sum_{in}\dot{m}_{in}\psi_{in} - \sum_{out}\dot{m}_{out}\psi_{out} \qquad (1)$$

where, for an ideal gas with negligible changes in potential and kinetic energy,

$$\psi = h - h_0 - T(s - s_0) \qquad (2)$$

The net exergy loss in the airspace of the data center is obtained by summing the exergy destruction in the individual cells of the mesh. It can be seen from Eq. (1) and (2) that the only quantities required (other than rack power consumption) to determine exergy loss are the mass flowrates and temperature distribution throughout the system, which are both measurable quantities. A more detailed description of exergy modeling in data centers and related considerations has been given by Shah et al [11].

System Description

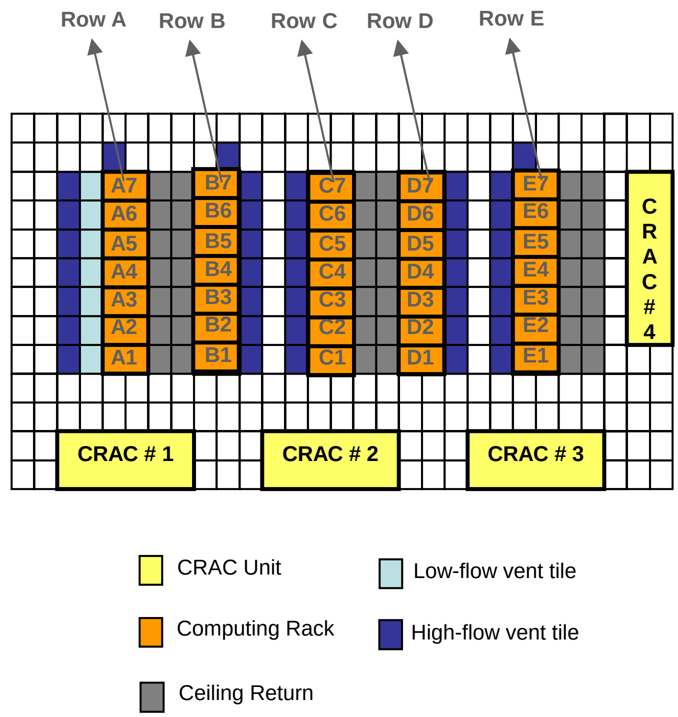


**Figure 3**. Layout of experimental data center.

Figure 3 shows a layout of the system utilized in this study. Each tile covers an area of 2' x 2'. The ceiling height is 9' measured from the floor, with an additional 4' in the ceiling return plenum and another 2' depth in the floor supply plenum. For purposes of simplicity, the model summarized in this paper was restricted to the sub-ceiling region above the floor plenum, but additional layers can be added if so desired. Each cell was considered to have the same area as one floor tile (i.e. 2' x 2'), and the data center was divided into the four regions shown in Fig. 2. Ceiling return mechanism was considered for all experimental and modeling cases, with the locations of return vents noted in Fig. 3.

Air is supplied from four 30-ton Liebert FH600C-AAEI CRAC units, each of which has a maximum air flowrate of 29,070 $m^3$/hr (17,100 cfm) per manufacturer specifications. The air enters the room either through low-flow vent tiles (which have dampers that restrict maximum throughput to 750 cfm) or high-flow vent tiles. The exact magnitude of flow through each tile is a function of plenum pressure, and is assumed to be a known quantity for modeling purposes.

Heat input is provided from five rows of computing racks. The heat dissipation from each rack is specified using rack power measurements or from manufacturer specifications.

Thus, this study uses the variables of rack power consumption (heat load), CRAC fan speed and air supply temperature as input parameters to the model and as control parameters for the experiment. A base case scenario for the model was run with all of the CRAC units operating at 100% fan speed at a supply temperature of 18 $^{o}$C. As described in the next section, the results from the model can be compared to experimental data collected from the actual data center to assess the accuracy of the model.

## EXPERIMENTAL VALIDATION

The exergy-based data center model essentially performs three computational operations in sequential order:

- Flow approximation (based on conservation of mass),
- Temperature estimation (based on energy balances),
- Determination of system exergy content and loss (based on flow and temperature maps).

To develop an estimate for the overall performance of the model, it is beneficial to consider the accuracy achieved at each of these individual stages.

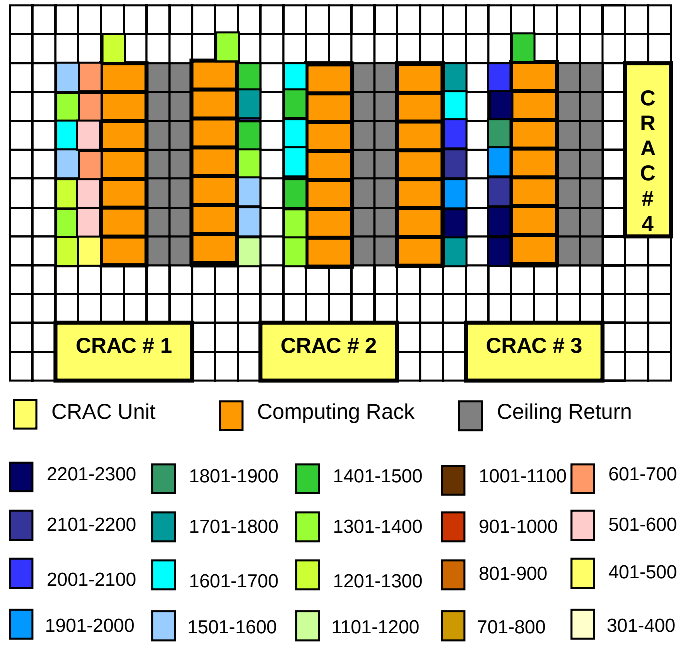


**Figure 4**. Inlet flow distribution (in cfm) measured with flow hood at supply vent tiles.

<u>Flow Approximation</u>

The input flow conditions for the data center were made using measurements from a flow hood (accurate to within 10% of actual values). Figure 4 shows a map of the average flow estimates thus obtained. Having obtained the inlet flow conditions, the model was run to obtain approximations throughout the system. To compensate for increased flow conditions at the rack units, a local massflow was calculated based on an estimated inlet-outlet temperature difference for a given rack output:

$$\dot{m}_{rack} = \frac{\dot{Q}_{rack}}{C_p\left(T_{rack,out} - T_{rack,in}\right)} \qquad (3)$$

To verify the accuracy of flow approximations obtained in the model, measurements were made with a hand-held anemometer at several locations in the room. The points of data collection were chosen to allow for assessment of model performance at different key locations of the system, including rack inlet, rack outlet, CRAC return, and potential hotspots in the hot aisles. Additional measurements were also made in the cold aisles to assist in the identification of locations of recirculation or short-circuiting. The exact locations of data measurement have been shown in Fig. 5.

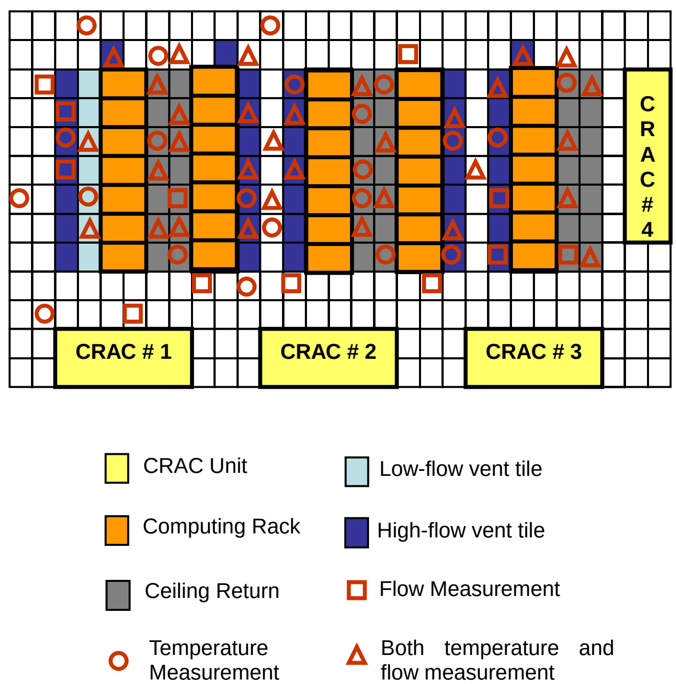


**Figure 5**. Points of data collection in the system.

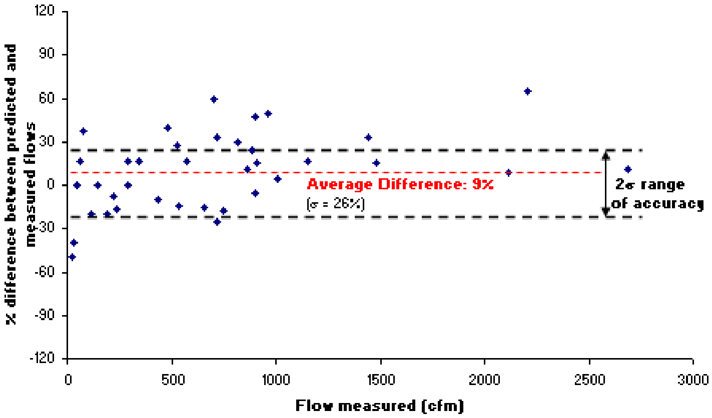


**Figure 6.** Comparison of predicted and actual values for massflow approximation.

Figure 6 shows a comparison of actual and predicted flow distribution for the modified model. The average difference is less than 10%, and the standard deviation is only 26% (i.e. 68% of the predictions agree with measured values to within 26%). Considering that measurements using the handheld anemometer are accurate to within 20%, if the targeted mean is adjusted to the desired value (i.e. a mean error of 0%), then the range of flow predictions by the model can be estimated to be accurate within 35%, an acceptable range of values for a first approximation. If further accuracy is desired, then finer meshes or more accurate techniques such as CFD should be used.

Temperature Estimation

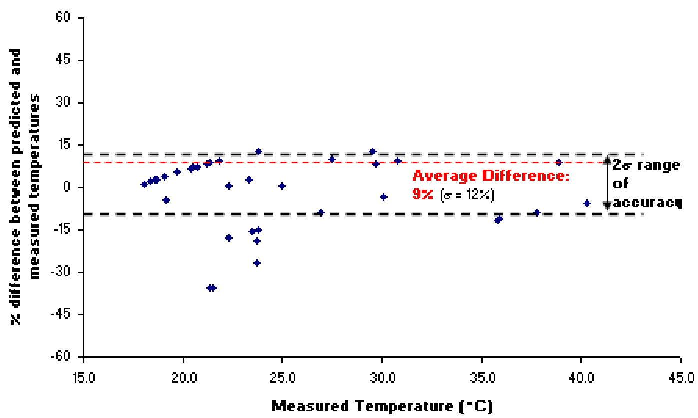


**Figure 7.** Comparison of predicted and actual values for temperature estimation.

The experimental procedure for validation of temperature prediction is similar to that described earlier for flow approximation. Hand-held thermometers and type-K thermocouples (accurate to within +/– 1 $^{o}$C per manufacturer specifications) are used to obtain temperature readings at the data collection points specified earlier in Fig. 5. Additionally, actual flow values (measured using the hand-held anemometer) rather than estimates at rack inlet and outlet locations are provided as input for temperature calculations. A comparison of predicted and actual temperature values is shown in Fig. 7.

Although not immediately evident, an investigation of the raw data indicates that the temperature trends captured by the model in the hot aisle are similar to those observed in the actual data center. However, the magnitude of temperature predictions is inaccurate, and the trends in the cold aisle are not captured well. This could be because the massflow approximations in the model do not account for pressure differences (which are important in recirculation effects). Alternatively, this could also be because of procedural error in experiment rather than error in prediction – for example, if the thermocouple may have been lying in an area of turbulent flow above the vent tile, the measurements will not be as reliable. In either case, the 2σ band of data is narrow enough where most of the temperature predictions fall within an acceptable target range. Further accuracy can be achieved by considering additional factors such as static pressure distribution, rack height, row width etc in the model, which can potentially be accounted for through non-dimensional characteristics such as the Supply Heat Index (SHI) or Return Heat Index (RHI) [13].

System Exergy Content and Loss Rates

Exergy loss is calculated in the model based on system temperature and flow values, and since both of these two quantities have already been validated, it is expected that predictions for exergy loss will also be within the same limits of accuracy. Modeling results suggest that exergy destruction is highest in the middle of rows (where maximum flow gets recirculated over the top) and at the end (where recirculation occurs both around the side as well as over the top). These predictions qualitatively agree with observations of inlet temperatures in the actual data center [14], thereby lending credibility to the predictions from the model. Nonetheless, to obtain a quantitative estimate of model accuracy with regards to prediction of trends of exergy destruction, an indirect estimate of the total exergy destruction in the physical airspace was calculated based on the exergy loss occurring in other parts of the system. For example, the exergy loss in the rack units can be measured based on power consumption measurements for the racks. Similarly, the measurements of CRAC supply/return temperature and flowrate allow us to calculate the total exergy loss occurring in the CRAC units. Assuming that the physical airspace is the only remaining mode of exergy loss in the system, an estimate for the exergy destroyed in the airspace can be obtained as follows:

 

$$\Psi_{d_{airspace}} = \Psi_{\substack{ini\\air}} + \Psi_{sup} - \Psi_{d_{CRAC}} - \Psi_{d\,racks} \qquad (4)$$

The exergy loss computed using Eq. (4) will not be exact, since some phenomena (such as exergy loss due to heat escape through walls) will not be accounted for. However, the magnitude of these losses will be small, and as shown in Fig. 8, estimates from Eq. (4) compare quite well to those predicted by the model for a variety of scenarios. Note that the uncertainty bar for the estimated values has been calculated based on the $2\sigma$ range of data, while the uncertainty bar for the predicted values has been calculated based on average accuracies obtained earlier for temperature and flow approximations.

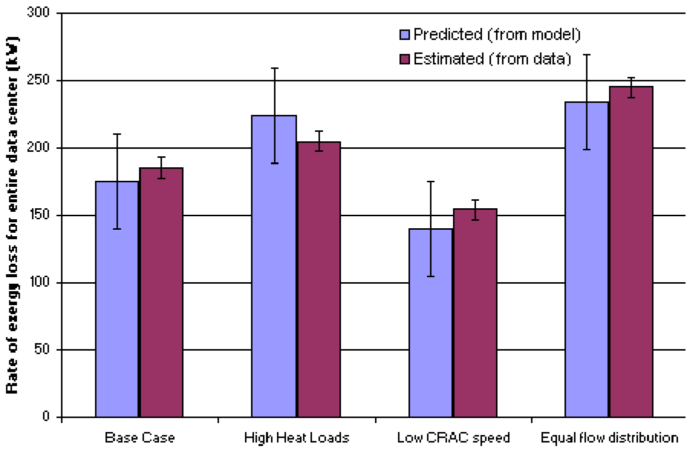


**Figure 8**. Estimated accuracy of model for exergy loss predictions.

In addition to documenting the variability in prediction of the proposed model, Fig. 8 also provides insight into the functionality and utility of such a tool. For example, by characterizing the total rate of exergy loss in the data center for various configurations, it becomes possible to investigate the impacts of different parameters on the overall system performance. Figure 8 suggests that for the given data center layout, the optimal performance occurs at standard heat loads and low CRAC speeds (which should not be surprising, since the blowers of the CRAC consume very large amounts of power). Another interesting observation is the increased exergy loss if the flow input is equally distributed (rather than the unequal input shown earlier in Fig. 4). In other words, the recirculation effects are worse if equal amounts of flow enter all the vent tiles – an observation that can be realized through CFD modeling [15], but has efficiently been captured by the current approach as well.

## CONCLUSIONS

Recent heat load trends in data centers indicate a need for revised thermal management techniques. A recent approach has been suggested based on the concept of exergy, but no actual data has been gathered regarding the utility of this approach to-date. This paper has reviewed the proposed exergy-based methodology for the analysis of cooling systems in data centers, and has discussed the development of a computer model for an instrumented data center in Palo Alto, California. While the modeling initially seems straightforward, experimental validation efforts suggest that several subtleties unique to specific data center architecture exist that can cause unanticipated error in predictions. Calibration of the model for the data center is important, it has been estimated that an appropriately validated model will yield predictions for exergy loss that are within 35% of actual values. Greater accuracy can be achieved if desired through finer meshes (but increased computational time) or a combination of techniques (such as flow and temperature prediction from CFD with exergy loss prediction as proposed in this paper).

The effect of various parameters on the overall system performance has been characterized through an exergy loss, which provides insights into system performance that are difficult to intuitively perceive. Such a metric can be useful in computing a data center figure-of-merit through a MIPS per kW exergy loss or similar ratio as proposed by Patel [16]. Thus, at a minimum, the approach outlined in this paper provides a tool for the removal of inefficiencies in data center cooling systems and airflow patterns; at best, such an exergy-based tool can become the foundation for evaluating data center performance on a global basis.

## ACKNOWLEDGMENTS


The authors would like to thank Ratnesh Sharma and Monem Beitelmal of the SmartCool team at Hewlett-Packard Laboratories for their continued support and input to the project. Additionally, the authors are grateful to Tim Boucher and Aaron Wemhoff of the University of California, Berkeley for their assistance in the experimental process.

The work presented in this paper was made possible by a generous gift from the Hewlett-Packard Company through the Center for Information Technology Research in the Interest of Society (CITRIS) at the University of California.


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